PRELIMINARY RESULTS OF DOUBLE-SAMPLE FOREST INVENTORY OF PINE AND MIXED STANDS WITH HIGH- AND LOW-DENSITY LIDAR

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Abstract—LiDAR data (0.5 and 1 m postings) were used in a double-sample forest inventory on the Lee Experimental Forest, Louisiana. Phase 2 plots were established with DGPS. Tree d.b.h. (> 4.5 inches) and two sample heights were measured on every 10th plot of the Phase 1 sample. Volume was computed for natural and planted pine and mixed hardwood species. LiDAR trees were selected with new algorithms and focal filter procedures and height computed as the z-difference between interpolated canopy and DEM surfaces. LiDAR-derived heights were regressed against ground estimates. D.b.h.-height and LiDAR ground-height models were used to predicted d.b.h. from adjusted Lidar height and compute ground and LiDAR estimates of basal area and cubic volume. Phase 2 LiDAR estimates in mixed stands were computed by randomly assigning heights to species classes using a Monte Carlo simulation. Regression coefficients for Phase 2 estimates of square foot and cubic foot volume were computed for combined species-product classes. Regression estimates for low-and high-density LiDAR combined volume were partitioned by species-product distribution of Phase 2 volume. There was no statistical difference between low- and high-density LiDAR estimates on the adjusted mean volume estimate (sampling errors of 10.41 percent and 11.75 percent).

INTRODUCTION

Light detection and ranging (LiDAR) is a new remote sensing tool that has the potential for use in the acquisition of measurement data for inventories of standing timber. LiDAR systems have been used in a variety of forestry applications (Lefsky and others 1999, Means and others 1999, Nelson and others 1988, Nilsson 1996) for the quantification of biomass, basal area, and tree-and stand-height estimates. Means and others (2000) used LiDAR to predict forest stand characteristics and suggested that LiDAR was a promising method for use in forest sampling because it allowed adequate measurement of structural attributes of a timber stand. Height estimations by Magnussen and Boudewyn (1998), Young (2000), and Harrington (2001) reported underestimates of 1 to 4 m. McCombs and others (in press) have developed algorithms and focal filter procedures to determine tree location and estimate tree height, and Collins (2003) is working on draping multi-spectral imagery over LiDAR canopy surface models for hardwood species identification. The objectives of this study were to investigate the use of LiDAR in forest inventory of pine and mixed stands and to test protocols for using LiDAR in a double-sample inventory procedure.

STUDY AREA

The study area (1,200 acres) was located on the Louisiana State University, Lee Experimental Forest near Bogalusa in Washington Parish, LA. Forests within this region are dominated by natural and planted stands of loblolly pine (*Pinus taeda*), natural shortleaf pine (*P. echinata*), and mixed hardwood stands of red oaks (*Quercus* spp.), sweetgum (*Liquidambar styraciflua*), and hickory (*Carya* spp.). The cooperative project with LSU was funded by the Mississippi State University Remote Sensing Technology Center (MSU-RSTC), and NASA Stennis Space Center.

METHODS

LiDAR Procedures

Airborne 1 acquired the small-footprint, multi-return LiDAR data of the study area in June 2002, with an Optech ALTM-1225 system to attain nominal posting densities of 1 m (one hit per m^2, footprint size of 0.213 m) and 0.5 m (four hits per m^2, footprint of 0.122 m) for up to five returns. The low-density data were obtained at an altitude of 1,067 m on a swath width of 609 m and the high-density data from 610 m on a 189- m swath. Each return consisted of a UTM (Zone 15, NAD 83) x, y, and z coordinate, where z was height above ellipsoid (HAE) in m. The LiDAR data sets were surfaced to produce first return canopy and last return digital elevation models (DEM) with 0.2 m- cell sizes using a linear interpolation technique. Tree locations and heights were determined with algorithms and focal filter procedures developed by McCombs and others (in press) that use a "variable search window radius based on relative density". These procedures use moving, simultaneous 2.5-, 4.0-, and 5.5-foot-radius search windows that choose tree height as the point that is higher than 85 percent of the surrounding maxima from one of the three search windows. Tree height was interpreted as the difference between canopy and DEM z-values at each tree location. Tree heights were converted to point coverages and clipped to sample-area boundaries using UTM coordinates to describe sample plot locations and sizes.

Inventory Design

The inventory design for this double-sample application involved the use of a series of circular plots 0.05 acre in size. One hundred and forty-one (141) Phase 2 and 1,410 Phase 1 plots were established within the study area. Every 10th plot was a Phase 2 ground plot with other plots being Phase 1 LiDAR plots (fig. 1). UTM coordinates were established at the center of each Phase 2 plot for navi-

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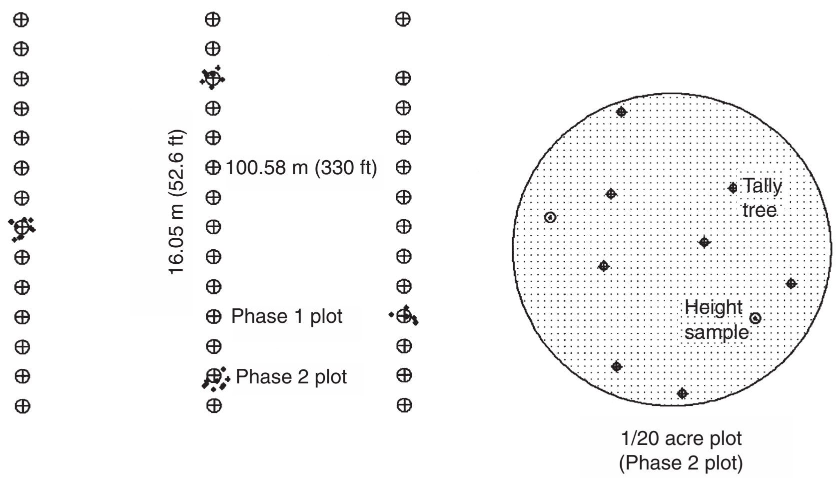

Figure 1—Plot and line design for Phase 1 LiDAR and Phase 2 ground (0.05 ac) plots for double-sample inventory of Lee Forest, Louisiana.

gation with real-time Differential Global Positioning System (DGPS). Differential corrections were obtained satisfactorily under the tree canopies by using a large dome antenna.

Ground data on Phase 2 plots included tree diameter at breast height (d.b.h.) on all trees > 5.5 inches in d.b.h. on the plot and total height on the two sample trees with minimum and maximum encountered d.b.h. and a crown class of dominant, co-dominant or intermediate. Ground data collection was completed for 141 Phase 2 plots in 2002, but LiDAR interpolations were completed for only 58 Phase 2 and 629 Phase 1 plots prior to this presentation. Thus, the preliminary results presented in this paper represent less than half of the study area and may not be indicative of the complete data set.

Double-Sample, Regression Estimator Model

The double-sample model widely used with ground-based point sampling (Avery and Burkhart 2002) and aerial photogrammetric inventories and adapted for this study was:

$$\bar{Y}_{lr} = \bar{y}_2 + \beta(\bar{X}_1 \;\; \bar{x}_2) \tag{1}$$

With traditional aerial photogrammetric inventories, the X_{1i} and x_{2i} variables are photo volume per acre and ground volume per acre from the Phase 1 and the Phase 2 plots, respectively, and β is the regression slope coefficient for y_i (ground volume per acre) over x_{2i} (LiDAR volume per acre on ground plot).

LiDAR is a new remote sensing tool that provides relatively precise measures of x-y-z UTM coordinates that can be surfaced and interpolated to produce estimates of heights and numbers of trees. Since there is only digital data, any estimate of basal area and volume must be derived from the height estimates as predictors of d.b.h. In this study, Phase 2 tree measures of d.b.h. and height were used to derive LiDAR estimates of basal area (square feet) and volume (cubic feet) by using d.b.h.-height equations to predict d.b.h. and basal area, and using the d.b.h. and height in a standard, standing-tree volume equation to predict volume (cubic feet). Thus, the double-sample models used in this study involved LiDAR mean estimates of basal area (LiBA) and volume (LiVOL) for the x-variables as:

$$\bar{Y}_{lr} = \bar{y} + \beta(LiBA - liba) \tag{2}$$

$$\bar{Y}_{lr} = \bar{y} + \beta(LiVOL - livol) \tag{3}$$

DATA ANALYSIS

The per-acre number of trees, basal area, and volumes for 58 Phase 2 ground plots and total heights of trees for 629 Phase 1 low-density LiDAR plots and 611 high- density LiDAR plots were computed and stored by plot number in text-data format for subsequent use in a spread sheet and custom software.

Phase 1 Plots

LiDAR height was adjusted to ground height for high-and low-density LiDAR estimates with the combined species models:

High-Density LiDAR: $H_{h,gr} = 2.4716 + 0.9788\, H_{h,Li}$ (4)
(I^2 =89.9)

Low-Density LiDAR: $H_{l,gr} = 2.9930 + 0.9758\, H_{l,Li}$ (5)
(I^2 =87.7)

where $H_{h,Li}$ is estimated height with high-density LiDAR, $H_{l,Li}$ is estimated height with low-density LiDAR, $H_{h,gr}$ is measured ground height of trees on high-density LiDAR plots, $H_{l,gr}$ is measured ground height on low density LiDAR plots, and I^2 is the statistical index of fit. D.b.h. and height from the ground plots were fitted to the combined species, d.b.h.-height model:

d.b.h. $= 2.3930 + 0.000179\, [\mathrm{Ln}(H_{gr})]^{7.4808}$ (6)
(I^2 =76.1)

where H_{gr} is ground height of measured trees.

Phase 2 Plots

LiDAR height was adjusted to ground height for high- and low-density LiDAR estimates with the following pine and hardwood models:

High - Pine: $H_{h,gr} = 3.8390 + 0.9689\ H_{h,Li}$ (I^2 =90.2) (7)

Low - Pine: $H_{l,gr} = 3.2505 + 0.9792\ H_{l,Li}$ (I^2 =88.0) (8)

High- Hardwood: $H_{l,gr} = 5.2776 + 0.8909\ H_{l,Li}$ (I^2 =78.2) (9)

Low - Hardwood: $H_{l,gr} = 8.3140 + 0.8392\ H_{l,Li}$ (I^2 =78.6) (10)

Tree d.b.h. was computed with the ground height models for pine and hardwood:

Pine: $d.b.h._{pine} = 1.1032 + 0.00064771[Ln(H_{gr})]^{6.6747}$ (I^2 =78.7) (11)

Hardwood: $d.b.h._{hdwd} = 2.8956 + 0.00006391[Ln(H_{gr})]^{8.2591}$ (I^2 =72.5) (12)

LiDAR Basal Area and Volume on Phase 2 Plots

Basal area and volume on the Phase 2 LiDAR plots were obtained by randomly assigning the LiDAR-derived tree heights to species percent distribution classes on each plot with a 500-iteration Monte Carlo simulation. Prior to the simulation, percent distribution by species-product class on each Phase 2 plot was ordered from largest to smallest. At each iteration, a new seed was selected from the time clock, and the randomly selected heights were randomly allocated to a species-product class. Once allocated to species-product class, the random LiDAR height was adjusted to ground height with equations (7) through (10) depending on species, and high-or low- density LiDAR and ground height were used to predict tree d.b.h. with equations (11) or (12), calculate basal area, and predict cubic foot volume with a standing tree volume equation. Average heights, basal areas, and volumes by species-product class for each ground plot for the 500 iterations were saved in text data format for subsequent combination with other plot data.

LiDAR Basal Area and Volume on Phase 1 Plots

Basal area and volume on the Phase 1 LiDAR plots were obtained by adjusting the LiDAR heights with equation (4) or (5), predicting d.b.h. with equation (6), and calculating basal area and volume. Assignments to species-product classes were not made on individual Phase 1 plots. Species-product volumes were subsequently obtained on the Phase 2 plots by partitioning the combined volume estimate into the respective species-product classes.

RESULTS

LiDAR vs Ground Height

The differences between ground measured and LiDAR estimates of height were significant (at $\alpha = 0.05$). High-density LiDAR heights had a bias of approximately -2.5 feet (equation 4), whereas low-density LiDAR heights had a bias of approximately -3.0 feet (equation 5). Height bias will result in differences in volume, but the volume differences can be “adjusted” with either the ground-LIDAR height equation prior to volume computation or with the regression estimator in the double-sample model if unadjusted heights are used to compute tree volume.

LiDAR heights are generally underestimated because the probability of a laser return from the terminal of conical-shaped crowns is very low. The narrower and more conical the crown, the greater the likelihood that the pulse return is from a portion of the crown below the terminal. It appears that heights from high-density LiDAR more closely approximated ground-measured heights than did heights from low-density LiDAR.

Phase 1 Relationships and Values

On Phase 1 plots, the composite species ground-LiDAR height and d.b.h.-height relationships were used to obtain combined per-acre estimates of trees, basal area, and cubic foot volume (table 1). The preliminary data suggests that low-density LiDAR produced higher estimates of numbers of trees than did high-density LiDAR or ground, thus resulting in higher estimates of basal area and cubic volume. These results were obtained with less than half of the Phase 1 and 2 plots.

Phase 2 Relationships and Values

Phase 2 ground and LiDAR volumes and basal areas for each species-product class are shown in table 2. The LiDAR volumes and basal areas for individual species-product classes were derived from the 500-iteration Monte Carlo allocation of heights. The random assignment of heights to species-product classes reasonably approxi-

Table 1—Phase 1 and 2 combined species, inventory results for per acre estimates of number of trees, basal area, and cubic foot volume from 629 high and 611 low density LiDAR plots (0.05 acre) vs. ground estimates from 58 plots on the Lee Experimental Forest, LA

Phase	Species	Product	High density LiDAR			Low density LiDAR		
			no.	*BA*	*ft³*	*no.*	*BA*	*ft³*
Phase 1 LiDAR	Combined	Combined	155	131	4,754	163	154	5,680
Phase 2 LiDAR	Combined	Combined	139	154	5,396	164	187	6,585
Phase 2 Ground	Combined	Combined	119	95	3,148			

LiDAR = light detection and ranging.

Table 2—Phase 2 inventory results for per-acre estimates of number of trees, basal area, and cubic foot volume from fifty eight–0.05 acre ground and high and low density LiDAR plots on the Lee Experimental Forest, LA

Species	Product	Ground			High density LiDAR			Low density LiDAR		
		no.	*BA*	*ft³*	*no.*	*BA*	*ft³*	*no.*	*BA*	*ft³*
Pine	Pulpwood	17	4	102	18	15	452	17	14	432
	Chip'n Saw	19	11	319	35	441	583	50	61	2,177
	Sawtimber	36	57	2196	33	48	1,724	48	70	2,486
Hardwood	Pulpwood	40	13	262	35	32	1,120	30	24	836
	Sawtimber	8	10	269	18	15	517	19	18	654
Combined	Combined	119	95	3148	139	154	5,396	164	187	6,585

LiDAR = light detection and ranging.

mated the actual ground distribution of volume and basal area, but it is apparent that LiDAR tended to overestimate numbers of trees per acre as compared to ground estimates. Overestimation of trees per acre resulted in overestimates of basal area and volume.

The regression relationships between ground and LiDAR basal area and volume were obtained from the Phase 2 data for combined species-product classes (table 3). LiDAR volume had a stronger relationship to ground volume than did LiDAR basal area, and low-density LiDAR relationships were stronger than high-density relationships.

Composite Species Double-Sample Estimates

Using double-sample model (3), the adjusted regression estimates of mean volume per acre and associated precision statistics for combined species-product classes with low- and high-density LiDAR are:

Low-Density LiDAR

$$\bar{Y}_{lr} = 3{,}148 + 0.2373\ (5{,}680 - 6{,}585) \quad (13)$$

$$= 2{,}933 \text{ cubic feet per acre}$$
(adjusted regression estimate of volume per acre)

$$S_{\bar{Y}_{lr}} = \pm\ 156 \text{ cubic feet} \quad (14)$$
(standard error of regression estimate)

S.E.= ±10.41 percent (15)
(sampling error @ 95 percent CL)

Table 3—Regression relationships and indices of fit for ground volume as a linear function of high and low density LiDAR volume per acre and basal area per acre for combined species on the Lee Experimental Forest, LA

Ground volume versus	β estimate	I²
High density LiDAR volume	0.2561	39.5
Low density LiDAR volume	0.2373	54.3
High density LiDAR basal area	10.2209	37.0
Low density LiDAR basal area	9.2671	53.6

LiDAR = light detection and ranging.

High-Density LiDAR

$$\bar{Y}_{lr} = 3{,}148 + 0.2561\ (4{,}754 - 5{,}396) \quad (16)$$

$$= 2{,}983 \text{ cubic feet per acre}$$
(adjusted regression estimate of volume per acre)

$$S_{\bar{Y}_{lr}} = \pm\ 179 \text{ cubic feet} \quad (17)$$
(standard error of regression estimate)

S.E.= ± 11.75 percent (18)
(sampling error @ 95 percent CL)

The double-sample estimate of adjusted mean volume per acre, linear regression, using low-density LiDAR volume was 2,933 cubic feet with a standard error of 156 cubic feet and 2,983 cubic feet with a 179 cubic foot standard error for high-density LiDAR. The 95 percent confidence interval ($\alpha = 0.05$) about each estimate overlaps the other estimate, so there is likely no statistical difference between the two values. It appears that the low-density LiDAR estimate resulted in a lower sampling error than did the high-density LiDAR estimate. Since these estimates are based on 58 of 141 Phase 2 plots and 629/611 of 1,410 Phase 1 plots, statistically valid comparisons can not be made at this time.

Partitioning of Double-Sample Composite Estimate

The double-sample volume estimate for combined species-product classes using low- and high-density LiDAR volume produced estimates of 2,933 cubic feet per acre and 2,983 cubic feet per acre, respectively. Since it is somewhat tedious to do a Monte Carlo simulation to randomly allocate LiDAR heights to species-product classes at the Phase 1 level, the partitioning of a composite species estimate into the various species-product classes using the Phase 2 plot distributions might be a reasonable alternative. The partitioning of the composite volume estimates from the LiDAR volume approach using percent distribution of volume is shown in table 4. Parker and Evans (in press) previously reported no difference between partitioning the composite double-sample volume estimate by percent occurrence of trees, volume, or basal area on the Phase 2 ground plots into individual species-class volumes and obtaining individual species estimates with their respective double-sample equations.

Table 4—Distribution of combined regression estimates of mean volume per acre from low and high density LiDAR by percent-volume distribution within species-product classes on Phase 2 plots of double-sample inventory area of the Lee Experimental Forest, LA

Species	Product	Distribution	Low	High
		percent	- - - - - *ft*^{3}	- - - - -
Pine	Pulpwood	3.24	95	97
	Chip n' saw	10.14	297	303
	Sawtimber	69.75	2,046	2,081
Subtotal		83.14	2,438	2,480
Hardwood	Pulpwood	8.31	244	248
	Sawtimber	8.55	251	25
Subtotal		16.86	495	503
Total		100.00	2,933	2,983

DISCUSSION

The double-sample regression estimates using LiDAR volume appeared to give reasonable volume estimates using the combined species-product approach even though less than half the data were analyzed. Precision statistics from the inventory provided reasonable validation data; however, these partial-sample results are inconclusive because of inadequate distribution of sample plots. Low-density LiDAR appeared best for estimating tree heights perhaps due to less bias and overall "noise". No statistical difference in numbers of trees between ground and LiDAR estimates was detected.

In single species stands, the problem of distributing heights and partitioning volume or basal area to species would not be present. In multiple species stands, the use of LiDAR basal area or volume in predicting double-sample estimates of volume should be investigated because either variable might be superior to the other. Parker and Evans (in press) found LiDAR basal area to be better than LiDAR volume in the Idaho study. However, the LiDAR posting spacing (2 m) was much lower on the Idaho site than it was on the Louisiana site (1 m and 0.5 m).

The combined species-product approach followed by distribution of resulting volume to individual species-product classes based on percent distribution of volume or basal area should yield similar results to the individual species approach. Procedures developed by Parker and Evans (in press) to randomly allocate the LiDAR heights to species-product classes in a Monte Carlo simulation worked reasonably well in this study. However, these procedures are being enhanced for subsequent analysis of the complete data set to allow allocation of Phase 2 LiDAR heights in a two-stage process—first to species class, then to product class with a check of d.b.h. merchantability limits.

LiDAR shows promise for forest inventory because it has the precision necessary to produce reliable estimates of trees per acre and standing tree height. Since d.b.h. is strongly related to height and stem density, reliable standing tree-volume estimates from LiDAR can be used effectively and efficiently in a double-sample design with traditional ground sampling methods to achieve inventory results at desired levels of precision. Biases in LiDAR heights and resulting basal areas or volumes or both are "adjusted" by the regression estimator in a double-sample model.

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